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Forest Ecology and Management 203 (2004) 251–259

Forest Ecology and Management

www.elsevier.com/locate/foreco

Post-fire regeneration variability of *Pinus halepensis* in the eastern Iberian Peninsula

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Received 4 November 2003; received in revised form 3 June 2004; accepted 21 July 2004

Abstract

Post-fire regeneration of *Pinus halepensis*, the most abundant tree in the Mediterranean Basin, can vary largely. In the present work, we aim to study the parameters determining this variability in the eastern Iberian Peninsula. For this reason we sampled in 2002 the sapling pine density on 22 plots that burned in 1993 and 71 plots that burned in 1994. Pre-fire vegetation (tree density and basal area) were obtained from the Spanish Forest Inventory. The regeneration ranged from 0.006 to 20.4 pines/m^2 (mean = 1.24, S.D. = 3.22). The statistical analysis suggested that the most important variables explaining this variability were the amount of branches found on the forest floor (branches collapsed from burned trees or branches left by foresters), the aspect of the plot, the pre-fire basal area, and whether the slope was terraced or not. High regeneration was observed in forests with large amounts of branches on the floor (which create appropriate microclimatic conditions), with northern aspects, with high pre-fire basal area, and on terraced slopes. Furthermore, other water-related variables (annual precipitation and slope) also had some (although lower) importance. These results have direct implications for forest managers in the study area.

Keywords: Aleppo pine; Canopy seed bank; Mediterranean pines; Post-fire; Sapling

1. Introduction

Fire is an integral part of Mediterranean and many other ecosystems (Kozlowski and Ahlgren, 1974; Pyne, 1995; Pausas and Vallejo, 1999). In particular, fire has become increasingly important in the eastern Iberian Peninsula, due to recent land-use and climatic changes (Pausas, 2004). *P. halepensis* (Aleppo pine), together with the closely related *P. brutia*, are the most widespread trees in the Mediterranean Basin (Quezel, 2000). At local scale, post-fire regeneration of *P. halepensis* woodlands has been studied elsewhere (e.g., Trabaud et al., 1985; Moravec, 1990; Saracino and Leone, 1993; Thanos et al., 1996; Daskalakou and Thanos, 1997; Ne'eman, 1997; Herranz et al., 1997; Martínez-Sánchez et al., 1999; Pausas et al., 1999, 2002, 2003; Arianoutsou and Ne'eman, 2000; Leone et al., 2000; de las Heras et al., 2002). In general, *P.*

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doi:10.1016/j.foreco.2004.07.061

halepensis regenerates profusely after fire due to the fact that this species stores a seed bank in the canopy (Tapias et al., 2001). However, at a regional scale, post-fire regeneration of this species may vary greatly (Tsitsoni, 1997), and in some areas it may be very low, threatening the persistence of the species in some Mediterranean areas. A review on the general characteristics of *P. halepensis* can be found in Ne'eman and Trabaud (2000).

Land managers aim to localise target areas where low regeneration is expected in order to reinforce post-fire reforestation actions (e.g., Vallejo et al., in press; Pausas et al., 2004). Previous works showed that the variability of fire severity within a fire may explain the different growth of pine seedlings, but not the amount of pine regeneration (post-fire seedling density) (Pausas et al., 2002, 2003).

The aim of the present work is to study the post-fire regeneration variability of *P. halepensis* in the eastern Iberian Peninsula. Our objectives were to quantify this variability and to study the factors that explain it. We concentrated on environmental and pre-fire vegetation

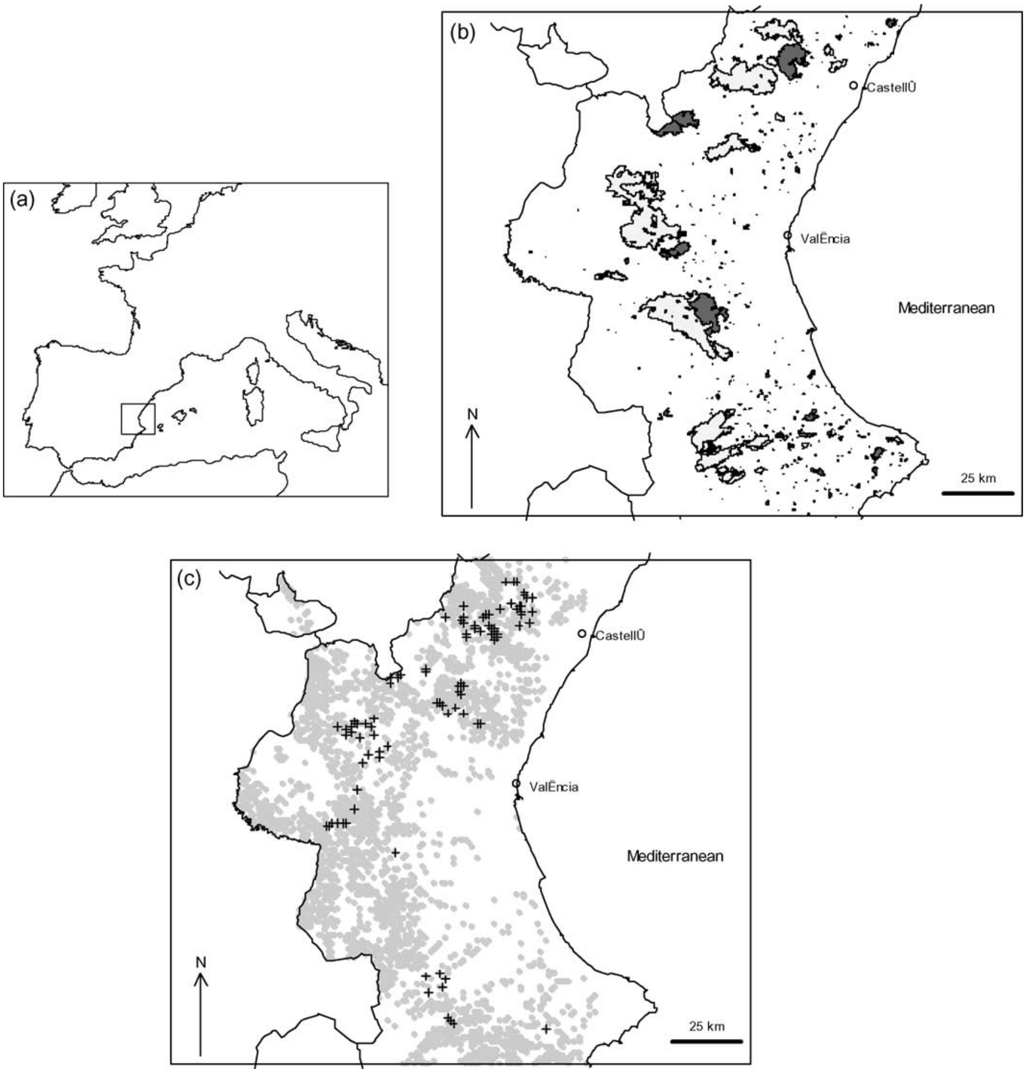

Fig. 1. (a) Location of the study area; (b) area burned in 1993 (dark grey) and in 1994 (light grey); (c) location of the sampled plots (crosses) and of the second Spanish Forest Inventory plots with *P. halepensis* (grey area).

factors; factors related to fire characteristics are not considered here (but see Ne’eman et al., 1992; Ne’eman, 1997; Pausas et al., 2002, 2003).

To answer the above questions, in 2002 we sampled pine woodlands that had burned in 1993 and 1994 in the Valencia region (eastern Iberian Peninsula). In these 2 years, the large fires that had occurred in this region had burnt ca. 26,000 and 140,000 ha, respectively (Fig. 1), i.e., ca. 13.5% of the forest area in the region (Pausas et al., 1999; Pausas, 2004). This large burned area is an excellent source of information for studying mid-term pine regeneration in different conditions.

2. Methods

2.1. Study area

The study area is inside the Valencia region, located in the eastern part of the Iberian Peninsula (Mediterranean coast, Fig. 1a). The climate is typically Mediterranean. Two predominant bedrock types occur in the area: limestone and marls. Limestones are calcareous hard rocks producing very shallow and decarbonated brown-red soils with abundant outcrops and cracks (*chromic Leptosols*, *ch. Cambisols* and *ch. Luvisols*). Marls produce deeper and highly carbonated soils but without cracks (*calcaric Cambisols* and *calcaric Regosols*). The vegetation is a product of a long history of fire and land use, and many slopes were terraced and cultivated in the past, then abandoned, and on some of these abandoned terraces, pines were planted. Thus, pine woodlands occur on both terraced and unterraced slopes.

2.2. Sampling

The sampling was made in areas with meso-Mediterranean climate (mean annual temperature: 13–17 °C) and an annual rainfall of 350–600 mm, as these features represent the typical conditions for pine woodlands in the study area. Using GIS techniques and the Second National Forest Inventory of Spain (SNFI), we localised 145 plots of mature *P. halepensis* stands the that fell within these climatic conditions. However, some were not found in the field, and others were disturbed after fire. Thus, a total of 93 plots were finally selected and sampled in 2002 (Fig. 1b); 22 had been burned in 1993 and 71 in 1994. We used the SNFI for pre-fire information on the pine woodland (pine density and basal area).

On each plot we counted the number of regenerated pines (*P. halepensis*) in two quadrants of a 10 m-radius circle (i.e., 157 m^2). Abiotic variables recorded for each plot were: bedrock type, slope, aspect, altitude, topographic position, amount of trunks and branches covering the soil (from collapsed trees or left after post-fire forest treatments), and distance to unburned woodlands (the latter two variables were recorded semiquantitatively, Table 1).

2.3. Data analysis

The number of regenerated pines was transformed into pine density (individuals/m^2). For statistical analysis, pine density was normalised using a logarithmic transformation (Fig. 2). Aspect was transformed to a quantitative aspect index (AI) related to moisture by assuming maximum moisture at NNE (winds coming from the west, i.e., inland winds, are drier than winds from the east, coastal winds). Thus,

Table 1
Independent variables used in the statistical analysis

Variable	Units/classes
Quantitative variables	
Pre-fire tree density	Individuals/ha
Pre-fire basal area	m^2/ha
Aspect Index	−1 to 1
Slope	%
Altitude	m a.s.l.
Mean annual temperature	°C
Annual precipitation	mm
Semiquantitative/qualitative variables	
Topographic position	Ridge (1), upper slope (2), mid-slope (3), bottom slope (4), gully (5)
Amount of branches on the soil surface	<1 (1), 1–25 (2), 25–50 (3), 50–75 (4), >75% (5)
Distance to unburned woodlands	<50 (1), 50–100 (2), >100 m (3)
Terraced	Yes (1), no (0)
Bedrock type	Limestone, marls, others

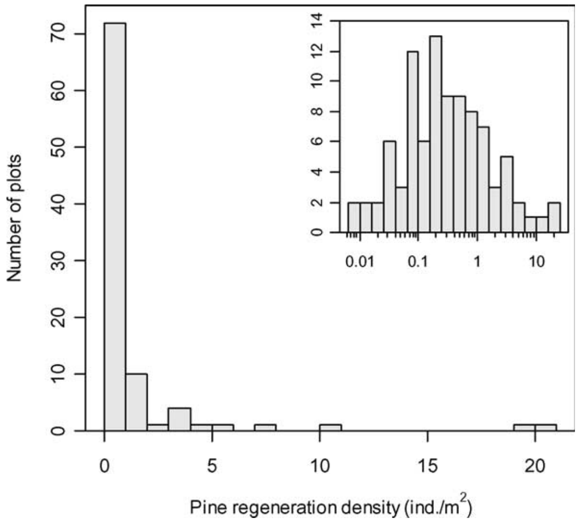

Fig. 2. Frequency distribution of regenerated pine densities (individuals/m^2). Inset graph shows the same data in logarithmic scale. Log-transformed distribution is not significantly different from a normal distribution (Shapiro–Wilk test, $W = 0.986$, $P = 0.46$).

the AI was computed as: $AI = \cos(\alpha - 22.5)$, where α is the facing angle in degrees east of north; AI ranges between 1 and −1. Direct incident radiation and heat load were computed from latitude, slope and aspect following the equations by McCune and Keon (2002); the three alternative equations proposed by these authors were tested. Mean annual temperature and annual precipitation were estimated from latitude, longitude and altitude using the weather station network and the CLIMAT software developed for the study area (Pausas, unpublished data).

Regression and ANOVA analyses were used to test the relationship between the regeneration (log-transformed) and the abiotic variables. Then, to find the parameters that explain most of the regeneration variability, we used a stepwise regression analysis of the regeneration (log-transformed regeneration density as dependent variable) versus the abiotic variables. Abiotic (independent) variables used (Table 1) were variables related to environment (macro- and microenvironment: bedrock type, slope, AI, altitude, topographic position, amount of branches on the soil surface) and variables related to seed input (pre-fire basal area, distance to unburned woodlands, and amount of branches on the soil surface). The amount of branches has an effect on both microclimatic conditions and seed input. Because AI was strongly correlated with radiation and heat load (for the three alternative equations, AI-radiation: −0.84, −0.85, −0.77; AI-heat load: −0.83, −0.83, −0.75) only AI (the simplest) was used in the stepwise regression analysis. Once we reached the best model, AI was substituted by the radiation and also by the heat load to test whether the variance explained could be increased by any of these parameters.

Regression residuals were analysed before accepting the regression model. Sites with high values with respect to any influential measure (residuals, covariance ratio and Cook's distance) were carefully checked for anomalies (Sokal and Rohlf, 1981).

Finally, the regeneration was classified as low (regeneration lower than the 25 percentile), intermediate, and high (regeneration higher than the 75 percentile) and evaluated with discriminant analysis in relation to the same abiotic variables as the regression, except the nominal variable (i.e., bedrock type). For discriminant analysis, topography, amount of branches and distance to unburned vegetation were used as semiquantitative variables (1–5, 1–6 and 1–3, respectively) and terraced as dummy variables (Table 1).

The use of two multivariate analyses, one based on a quantitative-dependent variable (multiple regression) and the other on a qualitative-dependent variable (discriminant analysis) ensures that we are finding appropriate explanatory variables and that the results are not artefacts of the methodology.

3. Results

Eight/nine years after fire, *P. halepensis* regeneration varied greatly on the different sites (mean = 1.24, S.D. = 3.22 individuals/m^2; Fig. 2). All plots had some regeneration (the lowest had 0.006 individuals/m^2); many plots (50%) had pine densities lower than 0.25 pines/m^2 (median), but some plots had regeneration densities of up to 20.4 pines/m^2 (Fig. 2).

Post-fire regeneration was significantly and positively related to pre-fire tree density and basal area, to the aspect index, and to the amount of branches covering the soil (Fig. 3; Tables 2 and 3). Regeneration was significantly higher on terraced versus non-terraced slopes, and negatively related to slope (Tables 2 and 3). Climatic parameters, altitude, topographic

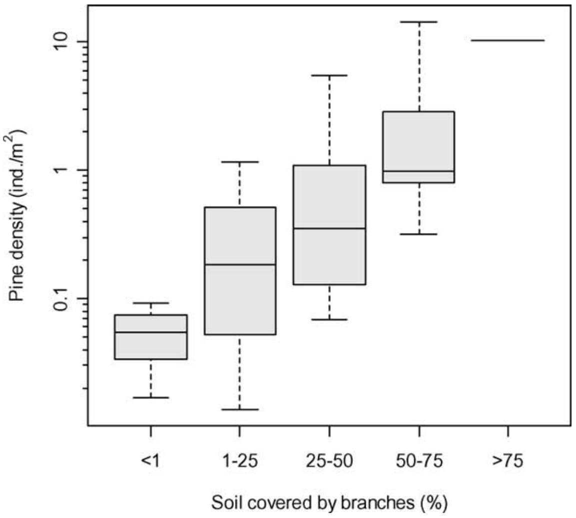

Fig. 3. Box-and-whisker plot of pine regeneration density (individuals/m^2, logarithmic scale) in relation to the proportion of the soil covered by branches. Boxes indicate the 25, 50 and 75%, and the whiskers the 5 and 95%.

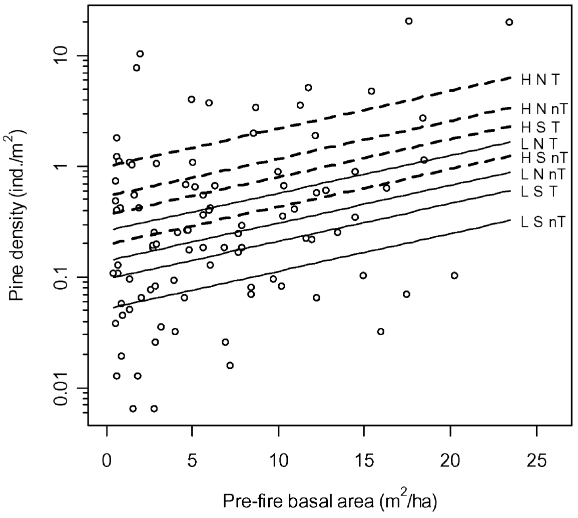

Fig. 4. Relation of post-fire pine regeneration density (individuals/m^2, logarithmic scale) to pre-fire pine basal area (x-axis), amount of branches covering the soil (L: low, 1–25%, continuous lines; H: high, 50–75%, dashed lines), previous land use (T: terraced; nT: non-terraced) and facing slope (N, S).

position and distance to unburned forest did not show any significant relationship.

There was a slight difference in regeneration between the sites burned in 1993 and those burned in 1994 ($F = 3.99$, $P = 0.049$); however, the difference was due to the fact that the plots burned in 1994 had significantly higher basal area than the plots burned in 1993 ($F = 7.58$, $P = 0.007$). When basal area is included as a covariant, the year (1993/1994) becomes non-significant.

Multivariate stepwise regression analysis suggests that part of the regeneration variability can be jointly explained by the amount of branches on the soil, the aspect index, the pre-fire basal area, and the previous land use (terraced versus non-terraced). The model with these four variables explained ca. 38% of the variability (Fig. 3, Table 4). The explained variance did not increase significantly when substituting the AI for any of the radiation or head load values obtained from the three alternative equations provided by McCune and Keon (2002), and thus, for simplicity, we opted for the simplest model that uses AI (Fig. 4).

Residuals of the multivariate model had a mean of 0.000 and a standard deviation of 1.34 and were not significantly different from a normal distribution

Table 2
Mean and S.D. of the stand characteristics and summary of the regression results in relation to post-fire pine regeneration density

Variable	Mean	S.D.	Regression coefficient	F	P
Pre-fire tree density (individuals/ha)	310	290	13.024	4.740	0.0321*
Pre-fire basal area (m^2/ha)	6.78	5.53	0.096	9.643	0.0025**
Pre-fire mean diameter (cm)	17.84	6.0	−0.001	0.114	0.736 ns
Aspect index (1 to −1)	0.10	0.73	0.640	7.264	0.0084**
Slope (%)	31.63	15.37	−0.024	4.246	0.0422*
Altitude (m)	638.40	185.21	0.0007	0.512	0.476 ns
Mean annual temperature (°C)	14.26	0.89	−0.173	0.739	0.3921 ns
Annual precipitation (mm)	541.09	50.87	0.0056	2.578	0.1118 ns

ns: $P > 0.05$.

* $P < 0.05$.

** $P < 0.01$.

Table 3
Summary of the one-way ANOVA for the five qualitative-independent variables in relation to post-fire pine regeneration density

Variable (classes)	ANOVA	
	F	*P*
Branches (1–5)	7.1709	0.0000****
Terraced (0/1)	7.3775	0.0079**
Topography (1–5)	0.9169	0.4578 ns
Distance (1–3)	0.0314	0.9925 ns
Bedrock (1–3)	1.4720	0.2350 ns

ns: $P > 0.05$.
** $P < 0.01$.
**** $P < 0.0001$.

($W = 0.98$, $P = 0.15$). Residuals did not show strong tendencies (increasing or decreasing) in relation to any independent variable. Nine sites were identified as having a relatively high residual or a high value of some of the influential measures. These sites were checked, but no anomaly was observed. Removing these sites, the model, the explained variance, and the coefficients remained roughly the same ($F_{5,\,78} = 8.63$, $P < 0.0001$, $R^2 = 0.36$).

Analysis of regeneration classes suggests that the first discriminant function, which accumulates most (89%) of the relative variance, segregates the plots with high regeneration from the plots with low regeneration (Fig. 5). Mean values of the first discriminant function are significantly different among regeneration classes ($F = 30.28$, $P < 0.0001$): −1.08, −0.04, and 1.19 for the low, intermediate and high regeneration class. The first discriminant function was strongly related to amount of branches, pre-fire basal area, land-use (terraced), aspect index and precipitation, and the second function was related to altitude, temperature and slope (Table 5). Thus, the discriminant functions were highly correlated with the same set of four variables selected by the regression approach, but two additional parameters (slope and precipitation) also show some (weaker) relation; precipitation was higher and slope lower in the higher regeneration class.

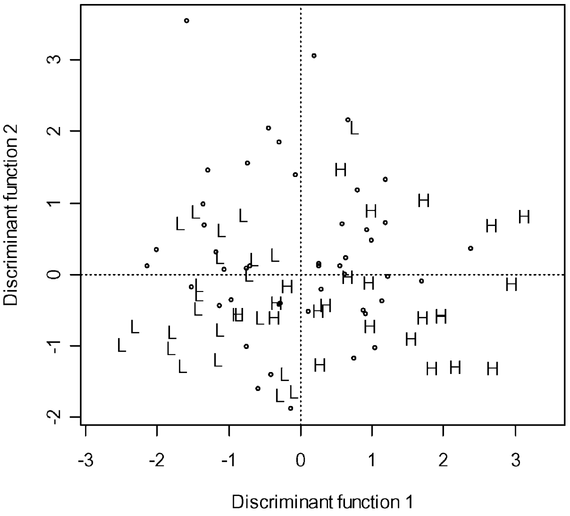

Fig. 5. Distribution of the plots in the two discriminant functions. L refers to plots with regeneration lower than the 25 percentile (0.083 pines/m^2) and H to the plots with regeneration greater than the 75 percentile (0.732 pines/m^2). The remaining plots are indicated with a dot.

4. Discussion

Pine regeneration in the study area, 8/9 years after fire, showed a large variability, ranging from 0.006 to 20.4 pines/m^2. Mean values (1.24 pines/m^2) were

Table 4
ANOVA table of the final multivariate model

	Df	Sum Sq	Mean Sq	*F*-value	*P*
Branches	4	66.483	16.621	8.346	0.0000****
Aspect index	1	14.416	14.416	7.239	0.0086**
Basal area	1	12.057	12.057	6.054	0.0159*
Terraced	1	8.216	8.216	4.125	0.0454*
Residuals	85	169.280	1.992		
Final (multiple $R^2 = 0.374$)	7.85			7.257	0.0000****

* $P < 0.05$.
** $P < 0.01$.
**** $P < 0.0001$.

Table 5
Correlation coefficients between the first and second discriminant function and the independent variables, and relative explained variance for each discriminant function

	Function 1	Function 2
Branches	0.746****	−0.056 ns
Terraced	0.497****	0.164 ns
Aspect index	0.468****	−0.279**
Basal area	0.366****	−0.037 ns
Precipitation	0.333***	−0.236*
Altitude	0.136 ns	0.615****
Topography	−0.064 ns	0.076 ns
Distance	−0.071 ns	−0.037 ns
Temperature	−0.159 ns	−0.593****
Slope	−0.251*	−0.541****
Explained variance (%)	88.86	11.14

ns: $P > 0.05$.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
**** $P < 0.0001$.

much lower than those reported by Tsitsoni (1997; 3.70 pines/m^2) in 8-year-old Greek stands in different topographic positions, but the range (variability) of our sites was larger than the one observed by Tsitsoni (0.3–17 pines/m^2, $n = 21$). Mean values were not very different from the pine density of 8-year-old post-fire woodlands in Catalonia (NE Spain, 1.00 pines/m^2; Papió, 1994) and in southern France (0.3, 0.5 and 1.5 pines/m^2; Trabaud et al., 1985), and higher than the 8-year-old woodlands in Mt. Carmel (near east, 0.275 pines/m^2; Arianoutsou and Ne'eman, 2000). Mean values were also much lower than the 5-year-old pine woodland from Albacete (SE Spain, 3.6 pines/m^2; de las Heras et al., 2002).

On many plots, the pine densities observed will probably be reduced as the pines get bigger. Pre-fire pine densities in the eastern Iberian Peninsula range from very low densities to ca. 1600 pines/ha (National Forest Inventory); on the studied plots, the highest pre-fire pine density found was 1200 pines/ha (mean = 311). Eight years after fire, 67% of the plots have more than 1200 pine saplings/ha. Thus, most plots with moderate or high regeneration will probably suffer further mortality (e.g., intra- or interspecific competition). About 20% of the plots showed a regeneration lower than 0.07 individuals/m^2 (700 pines/ha), and any mortality on these plots will produce low density woodlands.

Our analysis suggests that the main source of variation is the amount of branches and trunks covering the soil surface. These branches are from collapsed burned trees or from branches left by foresters when logging wood. These branches provide microclimatic conditions that favour the establishment of pines; they may also increase seed input by facilitating seeds getting out of the cone and reaching the soil. A manipulative experiment on this topic would be necessary to desegregate the effect of these two parameters and to quantify the change in microclimatic conditions and the associated increase in germination and establishment.

The amount of pre-fire pine biomass (measured as the pre-fire pine basal area) also showed a positive significant relation with regeneration. This may be due to the fact that the bigger the pine trees, the bigger the canopy seed bank, at least in the range of sizes and ages of the pines in the study area. Moister conditions (north-facing slopes, high AI) and terraced slopes (i.e., with flat areas and thus higher water retention capacity) also provide favourable conditions for pine germination and establishment in Mediterranean conditions. The discriminant analysis also suggests that additional water-related variables (precipitation and slope) may have some (although lower) importance. Tsitsoni (1997) suggested that *P. halepensis* tend to regenerate better at a low/middle position on the hillside and on moderate slopes or flat areas in northern Greece. However, in our study, topographic position did not show any clear pattern. This could be due, in part, to the fact that most of our plots were located at upper and mid-slope and very few were in ridges, bottom slopes and gullies. Thus, in our case, the main differences in water-related variables were not the topographic position but the aspect and whether the site was terraced or not (previous land-use).

The results suggest the main parameters that determine regeneration variability in the study area; however, a large part of the variability is still unexplained by the multivariate regression model. This unexplained variability may be partly due to sampling errors, but it may also be due to other factors not considered in this study. For instance, spatial variability of fire intensity and severity may not explain short-term post-fire seedling density but may explain different pine growth and mortality (Ne'eman et al., 1992; Ne’eman, 1997; Pausas et al., 2002, 2003) and thus, different mid- to long-term pine regeneration. Therefore, further research is needed in order to consider all factors simultaneously (environmental factors and fire characteristics) and be able to evaluate the relative importance of each parameter.

4.1. Implications for forest management

These results will help in determining the areas where poor pine regeneration after fire can be expected (e.g., south-facing unterraced slopes with low pre-fire pine biomass), and thus where emphasis on post-fire mitigation and restoration actions may be needed. By using information from forest inventories and land-use and slope maps, we could predict (and map) fire-sensitive pine woodlands, that is, woodlands that would regenerate poorly after fire; in these areas post-fire mitigation actions may be needed. Furthermore, some pre-fire management options (e.g., increasing the density of the fire-resilient species) in these sensitive areas could increase the resilience of the system.

Previous studies have shown that wood removal in *P. halepensis* stands does not threaten post-fire regeneration if the initial seedling density is large enough (Martínez-Sánchez et al., 1999), and has only marginal influence on the species richness and composition (Ne’eman et al., 1995). There has been much polemic among land managers as to whether or not the slash and tree branches resulting from forest actions are detrimental (for both aesthetic reasons and as a dead fine fuel for further fires) and, as such, should be removed. Our results provide evidence of the beneficial effect of branches on the soil surface; in fact, they could be used as a post-fire mitigation measure for enhancing regeneration in Mediterranean woodlands (Vallejo et al., in press; Pausas et al., 2004).

Acknowledgements

This work has been financed by the EU project SPREAD (EVG1-CT-2001-00043) and by an EU Leonardo da Vinci fellowship to E.R. Preliminary results were presented as part of SPREAD deliverable number D331. We thank A. Ferran, T. Gimeno and C. Beseler for their collaboration in the initial phase of the project and in the field sampling. CEAM is funded by *Generalitat Valenciana* and *Bancaixa*.

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